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REVIEW ON DESIGN GUIDE ON SMOKE MANAGEMENT SYSTEM FOR ATRIUM

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ABSTRACT

Design guides on smoke management in atria commonly used will be reviewed in this paper. Different approaches used in those guides are outlined. It is observed that the engineering principles on smoke dynamics behind these design guides are similar, though the basic approaches might be different. Smoke ventilation appears to be a common approach for smoke management in an atrium. An acceptable smoke layer height can be achieved or at least, the descending rate of smoke layer would be reduced. It should be noted that these guides can only give general principles for the design, but not necessarily covering all the atria. That is because only an efficient system with simplified design procedures for an ideal scenario is provided. Further guidance on solving practical problems frequently encountered is discussed.

Keywords: smoke management, atrium, design guide

1. INTRODUCTION

Smoke generated from a fire in an atrium itself or in spaces adjacent to the atrium may spread rapidly. Consequence will be quite serious in exposing a number of occupants to risk. The time for escape will be reduced and the fire-fighting activities will be affected, though the smoke will be quite 'cool' due to the large atrium space. Smoke management systems, which are defined as engineered systems including all methods that can be used singly or in combination to reduce smoke production or to modify smoke movement, are essential to provide a tenable environment for the safe evacuation of occupants [1].

Approaches to smoke management design in atria have been introduced into some codes or engineering guides. Guidance to designers of atrium smoke control systems within the UK appear in the British Standards BS 5588: Part 7 *Code of practice for the incorporation of atria in buildings* [2], CIBSE Guide E *Fire engineering* [3], the BRE Report 258 *Design approaches for smoke control in atrium buildings* [4] and BRE Report 368 *Design methodologies for smoke and heat exhaust ventilation* [5]. In the US, guidance on calculation procedures for the design of smoke in the atria are described in *NFPA 92B Guide for smoke management systems in malls, atria and large spaces* [1] and the design book *Design of smoke management systems* [6]. These guides will be reviewed in this paper. This would give some hints for engineers to select a workable guide by clarifying some uncertainties behind. The UK guides and the US guides will also be compared.

2. DESIGN OBJECTIVES

The selection of various design objectives and methods depends on the protection goals. Typical examples are on protecting the egress paths, on maintaining the areas of refuge, or on protecting the property. The following should be considered carefully [1,3,6]:

- Geometric shape and dimensions of the atrium;
- Building occupancy type and relative locations within the building;
- Degree of separation between atrium and associated floor area;
- Egress routes from the large-volume space and any communicating space;
- Relationship of the building to site boundaries.

Smoke management in an atrium normally includes management of smoke within the large-volume space and any spaces that communicate with the large-volume space. The source of the smoke can be a fire within the large-volume space or within the communicating space. In the fire safety design of atrium buildings, smoke management can be utilized to satisfy one or more of the following objectives:

- To maintain a tenable environment in the means of egress from large-volume building spaces;
- To control and reduce the migration of smoke between the fire area and adjacent spaces;
- To limit the rise of the smoke layer temperature and toxic gas concentration, and reduction of visibility;

- To assist the fire department personnel to approach, locate, and extinguish a fire.

3. DESIGN FIRE

The design fire has a broad impact on the estimation of hazard in smoke management in large spaces. The calculation of the quantity of smoke and heat produced by a fire requires the knowledge of the fire. Ideally, the design fire would be based on the materials within an occupancy. Unfortunately, although the heat release rates for many materials are known, it is rarely possible to say that a fire will consist of a known quantity of material.

A design fire can either be steady-state fire with constant heat output or unsteady fire with a time-dependent heat release rate.

- Steady fires

Steady-state fires for design calculation in various occupancies are given in the relative standards and these have usually been used historically. Although it is acknowledged that a real fire is not usually 'steady state', it is relatively simple to assess the maximum size a fire can reasonably be expected to reach during the escape period in a particular scenario, and to design a smoke control system which is able to cope with that. However, specification of a fixed design size applicable to all the fire situations is not feasible, any fire safety strategy must inevitably compare the time to the onset of dangerous conditions, which in turn depends strongly on the assumed fire growth rate, to the estimated evacuation time as well as to the attendance of fire-fighting services [1,3,5]. The time-dependent growing design fire has the attraction of trying to model the reality of growing time-varying fires.

- Growing fires

A t-squared fire can be viewed as an appropriate approximation for the growing fires in the design guides including NFPA 92B [1], CIBSE [3], *Design of smoke management systems* [6] and BRR Report 368 [5]. The heat release rate of the fire at any time is given by:

$$Q = 1000(t / t_g)^2 \qquad (1)$$

where t is the time after effective ignition, and t_g is the growth time, which is defined by the time taken for the heat output to reach 1055 kW. It has been suggested that fires may be conveniently classified as 'slow', 'medium', 'fast' and 'ultra-fast', depending on the characteristic growth time.

In reality, the growth rate may vary with time. Any actual sample of fires occurring in the same nominal occupancy will never be describable by a single growth curve. Producing a design fire curve requires knowledge about the burning rate of the object or combination of objects involved. This can be obtained from the literature or from intermediate scale tests of free burning items using large calorimeters. Where doubt exists regarding the accuracy of the curve to predict the outcome of a given design fire, higher burning rates should be selected in order to be conservative. Probabilistic analyses can also be employed in the development of design fire curves.

4. DESIGN APPROACHES

Several approaches are available to achieve smoke management goals in an atrium. Selection of the best smoke management approach for a particular atrium should consider the use, size, and arrangement of spaces. Most atrium smoke management systems are designed with the goal of not exposing occupants to smoke during evacuation. The following approaches can be used:

- Allowing smoke to fill the atrium space if the smoke filling time is sufficient for the safe evacuation of the occupants;
- Providing a smoke ventilation system to achieve a constant layer height for safe evacuation;
- Providing a smoke ventilation system to slow down the smoke layer descent rate to give sufficient time for safe evacuation;
- Providing opposed airflow or using smoke barriers to prevent the smoke spreading from the atrium into the communicating space or from the communicating space to the atrium.

a. Smoke ventilation

Smoke venting might be the common approach for smoke control in an atrium. Removing smoke from the atrium can limit the accumulation of heat and smoke within the atrium or can arrest the descent of the smoke layer. When the corridors, stairways, or other means of egress are located within the atrium or the communicating spaces are not separated from the atrium, using smoke venting to maintain the smoke layer at an acceptable height above the highest walking level or at a level higher than that of the highest opening to the communicating space for a specified would give a safety egress [1,6]. Two kinds of ventilation system – mechanical and natural ventilation system are often used.

b. Smoke filling

Smoke filling is another approach that can be applicable to some atria where the fire sizes are relatively small compared to the size of the space, the time taken to fill the space with smoke is relatively long compared to the time required for escape and firefighting. This approach is economic and can be particularly useful where there are adverse wind overpressures or it is difficult to incorporate vents or equipment into existing buildings such as historic buildings.

c. Limiting migration of smoke between the atrium and communicating space adjacent to the atrium

Using smoke barriers
Providing smoke barriers or draft curtains might be the simplest approach to limit the migration of smoke between the atrium and the communicating space. The smoke barrier should be airtight and resistant to the exposure of smoke. However, this approach might not be welcomed by the building designers, as the atrium cannot be utilized as a functional space, and the whole of the atrium is like a fire-resisting light-well [4,5].

Pressurization
Smoke barriers can be provided to limit smoke spread into the communicating space. In reality, the smoke barriers might not be airtight. A pressure difference might need to be applied across the smoke barrier to restrict smoke penetration. This method has been fully codified in the UK and USA and extensive guidance is available on its use.

Airflow approach
If physical barriers are not used, then the opposed airflow approach must be used in order to separate the communicating spaces from the atrium [1,6]. This method of smoke control has been widely used in the USA but less so in the UK.

5. CASE STUDIES

An atrium with height H of 15 m and cross-sectional area A of 250 m^2 was considered for the smoke control design. There is a compartment adjacent to the atrium at the ground level. The height of the compartment is 3.0 m, and the dimensions of the opening to the atrium are 5.0 m × 3.0 m (W × h). Only smoke management within the atrium space would be considered.

The following approaches will be considered:

a. Using passive smoke filling in the atrium space;
b. Using smoke ventilation system to maintain the smoke layer interface at a predefined height.

In each method, two fire scenarios would be involved:

- Fire occurs on the atrium floor;
- Smoke originates from the adjacent compartment.

Two types of design fire – steady fire and t-squared fire will be considered for the design. The fire size is assumed to be 2.0 MW, the perimeter of the fire is 5.6 m, and area of the fire is 3 m^2. Here, only fast or slow t-squared fire is considered. All of the designs assume a flat horizontal ceiling and a uniform horizontal cross-sectional area with vertical sides. Ambient air temperature is taken as 20°C.

For the smoke filling design, two calculation methods will be investigated:

Method 1: Using smoke filling equations (3) or (4) in NFPA 92B [1] to predict the position of the smoke layer interface under steady fire or unsteady fire respectively.

Method 2: Using the mass and energy conservation in the upper smoke layer, the position of the smoke layer interface is obtained by solving the following differential equation:

$$\rho_a A \frac{dz}{dt} + m_p + \frac{Q_c}{\rho_a C_p T_a A} = 0 \qquad (2)$$

where m_p is the mass flow of the plume. Axisymmetric plume equation and spill plume equation can be used respectively for the fire at the atrium floor or in the adjacent space open to the atrium.

Due to the large mass entrainment of the balcony spill plumes, smoke filling for the fire in the adjacent room is much faster than the fire on the atrium floor. Filling time for the slow t-squared fire is three times longer than that for the steady fire. Using steady design fire might give a conservative design when the smoke is the main hazard.

Variations of the position of the smoke layer with time predicted by the different calculation methods are presented in Figs. 1 to 3. For fire occurring on the atrium floor, it can be seen that a lower smoke layer interface position is predicted by equation (3) or (4) in NFPA 92B than by using method 2. This is because the position of layer interface in equation (3) or (4) only means the first indication of smoke, rather than the smoke layer interface position. Therefore, these two equations can provide a conservative estimate of the hazard. In addition, results predicted by equations (3) and (4) implicitly include the transport lag. For steady fire, equation (3) indicates a delay of approximately 5 s before a layer forms; for slow t-squared fire, this time will be greater as 12 s. While results predicted by using method 2 indicate immediate formation of the layer, this might not be true in real case. Especially for a slow t-squared fire occurring in spaces with large ratio of A/H^2, the transport lag may be appreciable. Ignoring the transport lag would yield a more conservative result as the smoke is instantaneously added to the upper layer, resulting in a more rapid layer descent.

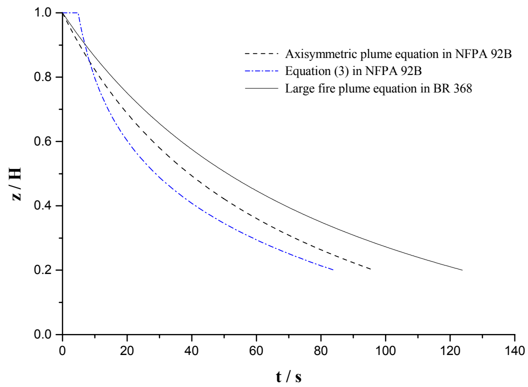

Fig. 1: Comparison of the smoke filling process predicted by different methods for steady fire occurring on the atrium floor

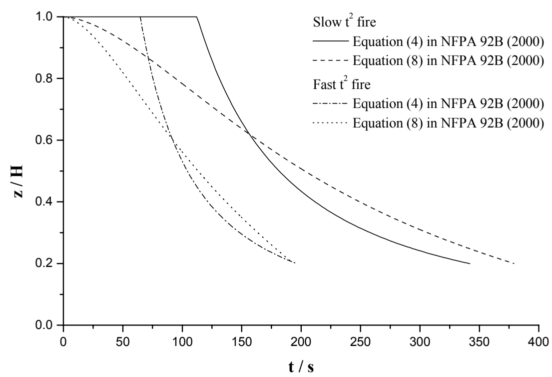

Fig. 2: Comparison of the smoke filling process predicted by different method for t-squared fire occurring on the atrium floor

Comparisons of the smoke filling predicted by different spill plume equations are shown in Fig. 3. Results predicted by BRE method were also found to be in close agreement with those predicted by NFPA equation under this design fire.

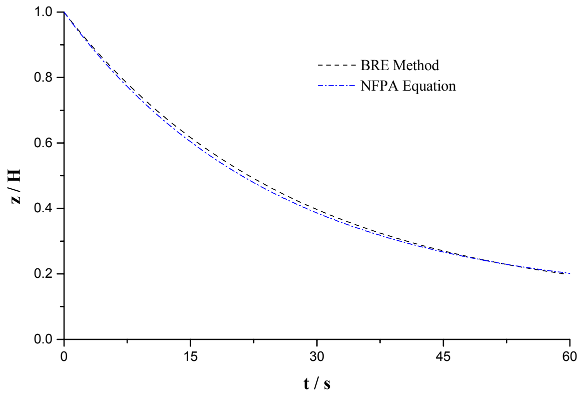

Fig. 3: Comparison of the smoke filling process predicted by different spill plume equations for steady fire occurring in the adjacent room

For the smoke filling design, occupants' evacuation should be analyzed. Provided that the available escape time is less than the required escape time, other smoke control measures should be provided.

For smoke ventilation design, exhaust rate should be determined for an acceptable design smoke layer depth. Exhaust rate calculated by different plume equations are shown in Table 1. It can be seen that larger quantity of smoke will be exhausted for fire originating in the adjacent compartment than for fire occurring on the atrium floor in order to maintain the same interface height in atrium. Lower layer interface height and lower extraction rate will be required. Different exhaust rate can be predicted by the NFPA equation and BRE equation. Large exhaust rate should be used to give a more conservative design in terms of safety.

6. CONCLUSION

Several design guides on smoke management in atrium were reviewed in this paper, key points can be summarized as follows:

- Smoke ventilation seems to be the primary approach for smoke management in an atrium. This approach has been codified in most design guides. Smoke filling is another approach which can be used when the time taken to fill the space with smoke is relatively long compared to the time required for escape and firefighting.

- Opposed airflow, depressurization and barriers are often recommended to prevent smoke flowing from the communicating space to the atrium, or from the atrium into the communicating space.

Table 1: Exhaust rate required for smoke ventilation

Design smoke layer depth (m)	For a fire in the atrium		For a fire in the compartment adjacent to the atrium	
	By NFPA plume equation (kgs^{-1})	By BRE plume equation (kgs^{-1})	By NFPA balcony spill plume equation (kgs^{-1})	By BRE spill plume model (kgs^{-1})
2	67.9	49.3	142.6	134.2
4	52.3	38.4	116.1	108.1
6	38.4	28.4	89.5	84.3
8	26.5	19.5	63.0	59.0

- Although most of the smoke control approaches in various design guides are the same, with the different calculation methods given in different guides, e.g. empirical equations for mass flow of fire plume in NFPA 92B and BRE report are not the same. For safety reason, conservative design should be recommended.

It should be noted that the design guides cannot cover all design possible for atria. Only general principles for the design of efficient systems can be provided, with simplified design procedures for an ideal model of an atrium. Further guidance on frequently encountered practical problems can be recommended. As the buildings become more complicated, both in size and geometry, scale models and CFD models are expected to be widely used for the smoke management system design in the future.

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